

DISCOVERY OF A CYCLOTRON RESONANCE SCATTERING FEATURE IN THE X-RAY SPECTRUM OF XTE J1946+274

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ABSTRACT

Observations of the transient accreting pulsar XTE J1946+274 made with the *Rossi X-ray Timing Explorer* during the course of the 1998 September–November outburst, reveal a cyclotron resonance scattering feature (or “cyclotron line”) in the hard X-ray spectrum near 35 keV. We determine a centroid energy of $36.2^{+0.3}_{-0.7}$ keV, which implies a magnetic field strength of $3.1(1+z) \times 10^{12}$ G, where z is the gravitational redshift of the scattering region. The optical depth, $\tau = 0.33^{+0.07}_{-0.06}$, and width, $\sigma = 3.37^{+0.92}_{-0.75}$ keV, are typical of known cyclotron lines in other pulsars. This discovery makes XTE J1946+274 one of thirteen pulsars with securely detected cyclotron lines resulting in direct magnetic field measurements.

Subject headings: stars: individual (XTE J1946+274) — stars: neutron — stars: magnetic fields — X-rays: binaries — X-rays: stars

1. INTRODUCTION

The transient accreting X-ray pulsar XTE J1946+274 was discovered during an outburst in 1998 September with the All Sky Monitor (ASM) on board the *Rossi X-ray Timing Explorer* (*RXTE*) (Smith & Takeshima 1998). At the same time, 15.8 second pulsations were observed with the *CGRO/BATSE*, with the pulsating source designated GRO J1944+26 (Wilson et al. 1998). The best X-ray position (*BeppoSAX*/MECS: 1' radius, 90% confidence, Campana et al. 1998) falls within the *Ariel V* error region for the transient source 3A 1946+274, making it likely that the two objects are identical (Campana, Israel & Stella 1999).

The initial outburst (see Fig. 2), which reached ~ 6 cps in the *RXTE*/ASM, lasted about 100 days and was followed by a series of smaller flares. Campana, Israel & Stella (1999) discussed the extended *RXTE*/ASM lightcurve, finding that the flaring was nearly periodic with a repetition period of ~ 80 d. They interpret this as either the half or full binary orbital period. Either case is consistent with the known orbital period range of Be/X-ray binary pulsars. Given its probable orbital period and the outburst characteristics, XTE J1946+274 is most likely another example of a Be star/X-ray binary pulsar transient. This class of binaries accounts for over half of the known accreting pulsars (Liu, van Paradijs & van den Heuvel 2000).

Several *RXTE* observations (see Figure 2) were made spanning the peak of the initial outburst. In this *Letter*, we report on the spectral analysis of these observations and, in particular, the discovery of a cyclotron resonance scattering feature, or “cyclotron line”, at ~ 35 keV. Santangelo et al. (2001) report their independent discovery of the XTE J1946+274 cyclotron line with *BeppoSAX* in this volume.

Cyclotron lines result from the scattering of X-rays by electrons in quantized Landau orbits in the $\sim 10^{12}$ G fields near the magnetic poles of accretion powered pulsars. The characteristic energy of the Landau transition scales with the magnetic field as $E_{cyc} = (11.6 \text{ keV})(1+z)^{-1} B_{12}$, where E_{cyc} is the cyclotron line energy in keV, z is the gravitational redshift in the scattering

region, and B_{12} is the magnetic field in units of 10^{12} G. Because of this proportionality, cyclotron lines give us the only direct measure of the neutron star magnetic field. In general, harmonically spaced lines (corresponding to higher order Landau transitions) may exist (see for example Heindl et al. 1999; Heindl et al. 2000; Santangelo et al. 1999). Depending on the temperature and geometry of the emitting and scattering material and the viewing angle with respect to the magnetic field, the line profiles may be broad and complex (e.g. Araya-Góchez & Harding 2000; Kretschmar et al. 2000). To date, about a dozen pulsars have well-established cyclotron lines, for the most part discovered with *Ginga*, *RXTE*, and *BeppoSAX* (see for example Makishima et al. 1999; Heindl et al. 2000; Dal Fiume et al. 2000).

2. OBSERVATIONS

During the XTE J1946+274 outburst, 12 pointed observations were made with the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE) on-board the *RXTE* (see Tab. 1 and Fig. 2). The PCA (Jahoda et al. 1996) is a set of five Xenon proportional counter units (PCUs) sensitive in the energy range 2–60 keV with a total effective area of $\sim 7000 \text{ cm}^2$. The HEXTE (Rothschild et al. 1998) consists of two arrays (“clusters A and B”) of 4 NaI(Tl)/CsI(Na) phoswich scintillation counters (15–250 keV) totaling $\sim 1600 \text{ cm}^2$. Early in the mission, the pulse height analyzer of a single cluster B phoswich failed, making the effective area of cluster B approximately 3/4 of cluster A. The HEXTE clusters alternate pointing between target and nearby blank fields in order to measure the background. The PCA and HEXTE fields of view are collimated to the same 1° full width half maximum (FWHM) region. In order to extend the life of the PCA detectors, most observations are currently made with one or more PCUs turned off. All the observations here were performed with PCUs 0, 1, and 2 on. Because PCUs 3 and 4 were sometimes off, they have been excluded from this analysis.

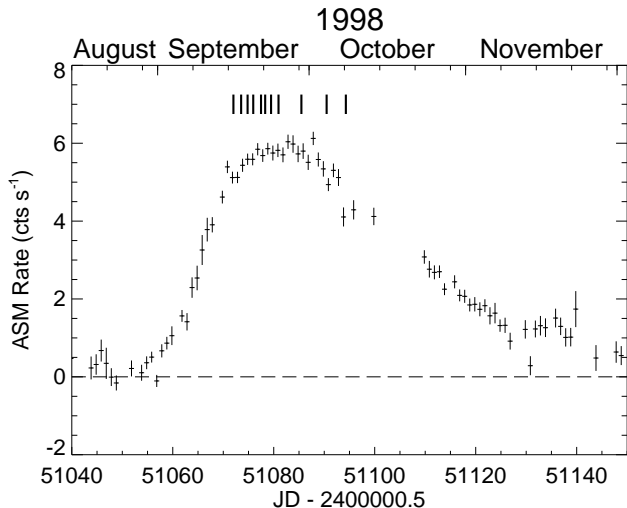


FIG. 1.— The *RXTE*/ASM lightcurve for the 1998 September outburst of XTE J1946+274. Bars at the top indicate the PCA/HEXTE observations (Table 1).

3. ANALYSIS

For each observation, we accumulated source and background spectra from the PCA standard 2 data and the HEXTE event mode data. We used the FTOOLS 5.0.1 and the procedures detailed by Wilms et al. (1999). In order to take advantage of the best PCA calibrations, we limited the data to detector layer 1 only. We summed the spectra for the 3 active PCUs to form a single pulse height spectrum. We used the bright source background model (appropriate for the counting rate of XTE J1946+274) to estimate the PCA background. Because of the high PCA counting rate of XTE J1946+274 and the duration of the observations, the statistical errors in the energy spectra ($\ll 1\%$) were small compared to the uncertainties in the instrument calibration. It was therefore necessary to include systematic uncertainties on the PCA data in order to achieve a reasonable fit to the data. We determined the size of these errors through the procedures recommended by the PCA team (Jahoda 2000) and explained in Coburn et al. (2001). In short, we fit contemporaneous observations of the Crab Nebula and Pulsar to a two power law model, using the XTE J1946+274 response matrices. This model allows for different power law indices for the pulsar and nebular components (Knight 1982). We adjusted the systematic errors until a reduced chi-squared of one was achieved – at a level of 0.3% per channel below 20 keV. Above 20 keV, the systematic errors became unacceptably large, $\gtrsim 5\%$, so we chose to ignore these PCA data, rather than apply large systematic errors.

We accumulated the HEXTE cluster A and B spectra separately then summed them to form joint source and background spectra for each observation. For the analysis of these summed spectra, we added the cluster A and B response matrices, weighted by the cluster effective areas (4:3, respectively). Fits with this matrix to a single power law model, appropriate in the HEXTE energy band, to the Crab have residuals of $\pm 1\%$. This is smaller than the statistical uncertainties, so we applied no additional systematic errors to the HEXTE data.

Because the observations were spread over ~ 1 month and a range of $\sim 40\%$ in flux, we were concerned that changes in the source spectrum could affect our analysis. To search for spectral changes, we calculated for each observation the ratio of the net PCA and HEXTE counts spectra to the total spectrum of all observations (see Figure 3). In all but observation 12, we

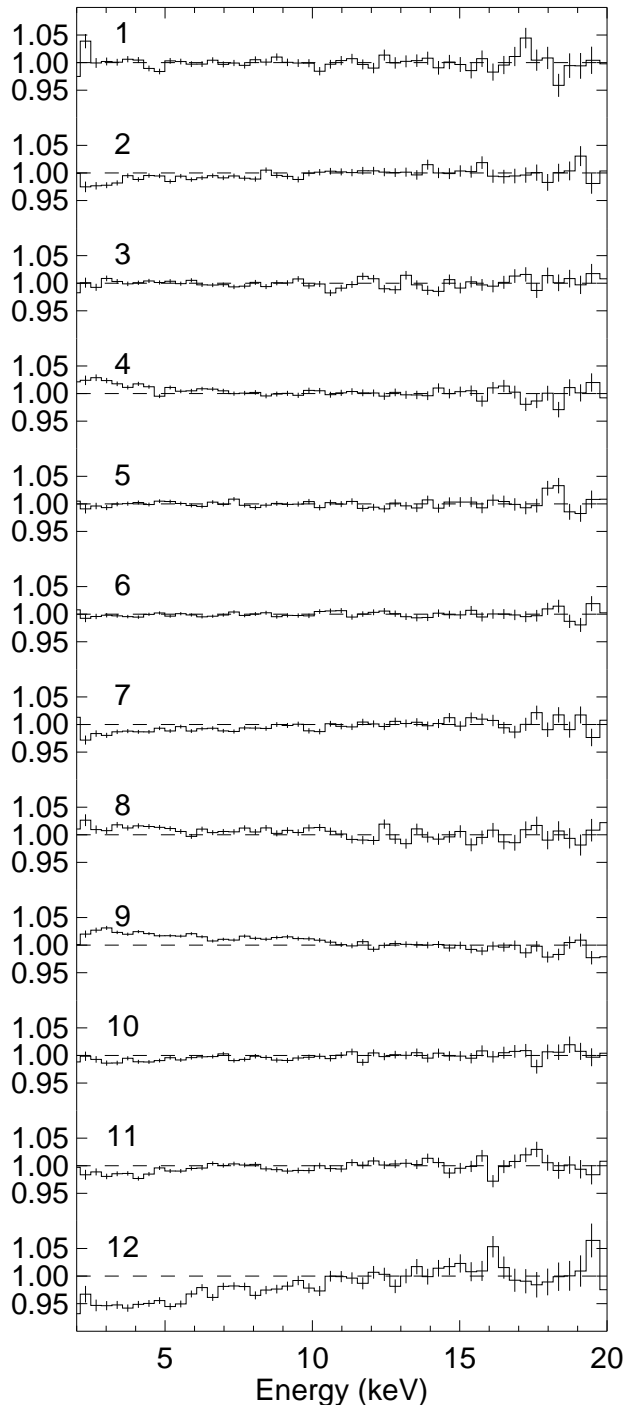


FIG. 2.— Ratios of the net PCA counts spectra from the twelve observations (Table 1) to the total spectrum, normalized to the 8–20 keV counting rate. While a small residual slope is apparent in observation 9, deviations above 8 keV were less than 2%, so this spectrum was included in the analysis. However, owing to the overall steep slope of its ratio and large deviations from one, observation 12 was eliminated.

found that above 8 keV, the ratio was nearly flat, indicating that only the flux, and not the spectral shape, had changed. In observation 12 (the last and dimmest observation – see Table 1), significant spectral changes were observed, and this pointing was eliminated from our analysis. Observations 1 to 11 showed no changes in spectral shape at a level of ~ 1 –2% between 8–20 keV. Below 8 keV, systematic changes of up to $\sim 5\%$ were

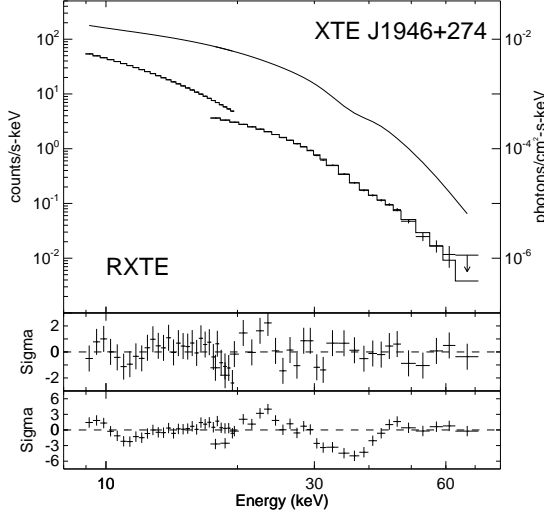


FIG. 3.— The joint PCA/HEXTE spectrum of XTE J1946+274. Top panel shows the data (crosses), the best fit NPEX model with a cyclotron line (histograms), and the inferred incident photon spectrum (smooth curve). See Table 2 for fit parameters. The middle and bottom panels show the residuals for the best fit model and the best fit NPEX model with no cyclotron line.

seen, particularly in the lowest energy channels. These changes are consistent with $\lesssim 10\%$ variations in the absorbing column and the iron line emission. Such variations are not unexpected during a Be/X-ray binary outburst, and they are likely not indicative of changes in the underlying continuum emission. The HEXTE ratios showed no evidence for spectral variability at a limiting level of $\sim 5\text{--}10\%$ below 35 keV. Above 35 keV the statistics did not allow for a meaningful comparison. For these

reasons, we concluded that by excluding data below 8 keV we could safely combine observations 1 to 11.

After accumulating observations 1 through 11 as described above, we attempted to fit the PCA and HEXTE spectra jointly with a set of continuum models typically used for accreting pulsars. While there is a notable lack of adequate theoretical models, pulsar spectra are heuristically well-described by a power-law at low energies which breaks to an exponentially cut-off power-law at high energies (White, Swank & Holt 1983). Kreykenbohm et al. (1999) review several models with this asymptotic behavior – the exponentially cut-off power law (PLCUT, White, Swank & Holt 1983), the Fermi-Dirac cut-off (FDCUT, Tanaka 1986), and a combination of two power-laws with a positive and a negative exponent (NPEX, Mihara 1995). None of these models provided an acceptable fit to the XTE J1946+274 spectrum. All models left significant, cyclotron line-like residuals near 35 keV (see Figure 3). We therefore added to each model a cyclotron absorption term with a Gaussian optical depth profile:

$$\tau(E) = \tau_{\text{cyc}} \times e^{-(E-E_{\text{cyc}})^2 / 2\sigma_{\text{cyc}}^2}. \quad (1)$$

Adding the Gaussian absorption line greatly improved the fits. The best fit was achieved with the NPEX continuum, given by:

$$\text{NPEX}(E) \propto (E^{-\Gamma_1} + \alpha E^{+\Gamma_2}) \times e^{-(E/E_{\text{fold}})} \quad (2)$$

where $\text{NPEX}(E)$ is the photon flux at energy E ; Γ_1 and Γ_2 are the indices of the falling and rising power law components, with α their relative normalizations; and E_{fold} is the exponential folding energy. Our best-fit model was of the form $\text{Flux} \propto \text{NPEX}(E) \cdot e^{-\tau(E)}$. In this case, the reduced χ^2 changed (with the addition of the line) from 3.61 to 0.97 for 52 and 49 degrees of freedom respectively. The resulting F -Test probability for this to be a chance improvement is 1.2×10^{-14} . Table 2 gives the best fit parameters for this model.

TABLE 1
OBSERVATIONS

	Date ^a	PCA		HEXTE	
		Time ^b	Rate ^c	Time ^d	Rate ^e
1	Sep 16	1.42	195.0 \pm 0.2	0.84	30.1 \pm 0.5
2	Sep 17	2.35	208.2 \pm 0.2	1.50	33.6 \pm 0.4
3	Sep 18	2.51	217.5 \pm 0.2	1.64	34.6 \pm 0.3
4	Sep 19	2.94	216.3 \pm 0.2	1.85	33.3 \pm 0.3
5	Sep 21	2.69	250.0 \pm 0.2	1.76	37.9 \pm 0.4
6	Sep 22	3.82	254.5 \pm 0.2	2.42	38.5 \pm 0.3
7	Sep 23	2.70	243.0 \pm 0.2	1.75	37.6 \pm 0.4
8	Sep 24	1.54	258.4 \pm 0.2	1.09	38.0 \pm 0.4
9	Sep 29	4.93	244.9 \pm 0.4	3.26	36.4 \pm 0.2
10	Oct 4	2.93	219.7 \pm 0.2	1.81	33.1 \pm 0.3
11	Oct 8	2.77	200.6 \pm 0.2	1.79	30.7 \pm 0.4
12	Oct 14	1.08	167.9 \pm 0.2	0.71	25.4 \pm 0.5
	Total ^f	30.6	230.7 \pm 0.3	19.7	35.3 \pm 0.1

^a 1998

^b exposure (ks)

^c cts s⁻¹ per PCU, 3–20 keV

^d exposure (ks)

^e cts s⁻¹, 16–100 keV

^f Observations 1 – 11. Observation 12 was excluded from the analysis (see §3).

4. RESULTS AND DISCUSSION

Figure 3 shows the best fit model and residuals together with the inferred incident photon spectrum. It also shows residuals to the best NPEX model without a cyclotron line, which is then apparent in the residuals around 35 keV. From the cyclotron line energy, we deduce a magnetic field strength in the scattering region of $3.1(1+z) \times 10^{12}$ G. The line is weakly resolved with the HEXTE energy resolution of ~ 8 keV (FWHM, at 35 keV), and the fitted width of the line is $9.3^{+2.5}_{-2.1}\%$ of the line energy. This is within the range of typical values determined with the Gaussian absorption profile model (Coburn 2001). No harmonic line near 70 keV was found, but as is evident in Figure 3, the falling high energy continuum provides inadequate statistics to make a sensitive search for such a feature.

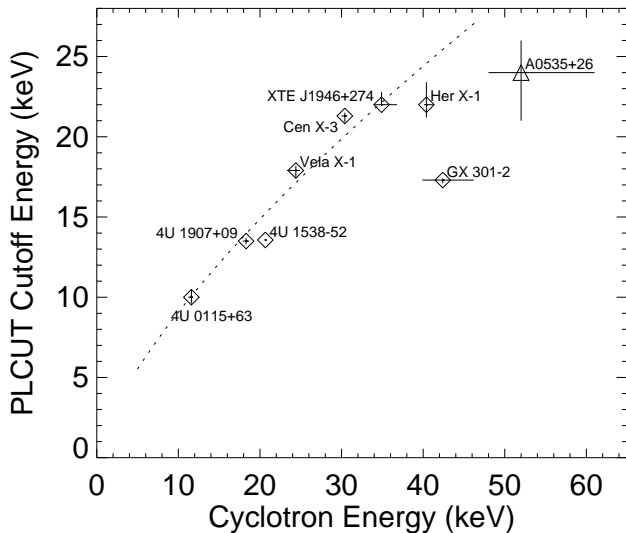


FIG. 4.— Spectral cut-off energy as a function of cyclotron line energy. A possible saturation of the correlation is seen at energies above 30 keV. All points are from *RXTE* except A0535+26 which is from HEXE/TTM (Kendziorra et al. 1994). The line is a power law with $E_{\text{cut}} \propto E_{\text{cyc}}^{0.7}$ (Makishima et al. 1999). See text for parameter definitions.

Figure 4 (after Coburn 2001) shows the spectral cut-off energy plotted against the cyclotron line energy for 8 pulsars measured with *RXTE*. Also shown is the (somewhat controversial) HEXE/TTM result for A0535+26 (Kendziorra et al. 1994). For uniformity, the pulse-phase average spectra of all sources were fit with the PLCUT continuum:

$$\text{PLCUT}(E) \propto E^{-\Gamma} \times \begin{cases} 1 & \text{if } E \leq E_{\text{cut}}; \\ e^{-(E-E_{\text{cut}})/E_{\text{fold}}} & \text{otherwise} \end{cases} \quad (3)$$

smoothed at E_{cut} (see Coburn 2001, for details). Two sources are excluded from the plot: 4U 1626-67, whose cut-off energy varies by a factor of four with pulse phase (Coburn 2001), and the low luminosity ($\sim 4 \times 10^{34}$ ergs s $^{-1}$) object 4U 0352+309 (X Per) whose spectrum is not well fit by the usual pulsar models. Due to the complex shape of the 4U 0115+63 fundamental line (Heindl et al. 2000), its plotted energy is half of the first harmonic value.

A clear correlation exists between the line energy and spectral cut-off indicating that the cut-off is related to the magnetic field. Makishima & Mihara (1992) and Makishima et al. (1999) first noted this relationship by plotting cyclotron line energies from *Ginga* and other instruments, derived with a variety of continuum models, against the PLCUT cut-off energy from sometimes non-contemporaneous *Ginga* observations. They found that the relationship was consistent with a power law,

$E_{\text{cyc}} \propto E_{\text{cut}}^{1.4}$ (or, $E_{\text{cut}} \propto E_{\text{cyc}}^{0.7}$), indicating a saturation as compared to a linear correlation. Figure 4 has the advantage that each point is derived from a uniform model fit to a single spectrum. And, with the exception of A0535+26, all points are from the same set of instruments. XTE J1946+274 fits nicely on the correlation, and below 30 keV, the slope is consistent with $E_{\text{cut}} \propto E_{\text{cyc}}^{0.7}$. However, there appears to be a break in the relationship above ~ 30 keV. This flattening is more abrupt than the smooth turnover of the $E_{\text{cyc}}^{0.7}$ power law suggesting that the processes that form the continuum saturate at higher magnetic fields.

With XTE J1946+274, we have added a 13th accreting pulsar to the list of objects with secure cyclotron line detections. Nearly all of these have been confirmed, and several were discovered, with *RXTE* and *BeppoSAX*. We have now begun detailed studies of these objects as a class. In particular, since ten of the thirteen sources have been observed with *RXTE*, we are applying uniform analyses to all these objects to further understand the line forming regions. First results of such studies, including correlations between other line parameters, are given in Coburn (2001).

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TABLE 2
 BEST FIT SPECTRAL PARAMETERS FOR AN NPEX TIMES GAUSSIAN ABSORPTION PROFILE MODEL.

Parameter	value
Continuum	
Γ_1	$2.80^{+0.14}_{-0.27}$
Γ_2	$-1.38^{+0.27}_{-0.10}$
α	$(3.1^{+3.2}_{-1.8}) \times 10^{-4}$
E_{fold} (keV)	$5.54^{+0.16}_{-0.13}$
Flux ^a	5.5×10^{-9}
Cyclotron line	
τ_{cyc}	$0.33^{+0.07}_{-0.06}$
E_{cyc} (keV)	$36.2^{+0.5}_{-0.7}$
σ_{cyc} (keV)	$3.37^{+0.92}_{-0.75}$
$\chi^2_r/\text{degrees of freedom}$	0.97/49

^a ergs cm⁻² s⁻¹, 2–10 keV